NASA/TM—2004-209317

Telescoping Mechanics: A New Paradigm for Composite Behavior Simulation

C.C. Chamis, P.L.N. Murthy, and P.K. Gotsis
Glenn Research Center, Cleveland, Ohio

S.K. Mital
University of Toledo, Toledo, Ohio

April 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-209317

Telescoping Mechanics: A New Paradigm for Composite Behavior Simulation

C.C. Chamis, P.L.N. Murthy, and P.K. Gotsis
Glenn Research Center, Cleveland, Ohio

S.K. Mital
University of Toledo, Toledo, Ohio

National Aeronautics and
Space Administration

Glenn Research Center

April 2004

Acknowledgments

It is to be understood that the order of the authors does not reflect their contributions in the development, implementation and validation of telescoping composite mechanics. Their contributions are about equal over time. Listed as first author indicates that he prepared the first draft of this article. It is also acknowledged that several other colleagues contributed. The authors express their gratitude and appreciation to them.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Telescoping Mechanics: A New Paradigm for Composite Behavior Simulation

C.C. Chamis, P.L.N. Murthy, and P.K. Gotsis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

S.K. Mital
University of Toledo
Toledo, Ohio 43606

Summary

This report reviews the application of telescoping mechanics to composites using recursive laminate theory. The elemental scale is the fiber-matrix slice, the behavior of which propagates to laminate. The results from using applications for typical, hybrid, and smart composites and composite-enhanced reinforced concrete structures illustrate the versatility and generality of telescoping scale mechanics. Comparisons with approximate, single-cell, and two- and three-dimensional finite-element methods demonstrate the accuracy and computational effectiveness of telescoping scale mechanics for predicting complex composite behavior.

Introduction

Composites contain several scales ranging from single-fiber, to multifiber ply, to multi-ply laminate (ref. 1). Formulations that simulate composite behavior are usually based on some intermediate observation scale between the most elemental (single-fiber) and the most complex (laminate). The most elemental scale was selected for simulation because it is simple to test and the tests are credible. Formulations based on the laminate observation scale, for example, are usually either material- or structural-configuration-dependent, or both, and tests must be repeated for every material or laminate. This approach is time consuming and costly. If the laminate response is taken as the observation scale, then the laminate theory based on known unidirectional composite (ply) properties is viewed as the mesomechanics scale. Micromechanics is considered the microscale, where formulation begins with constituent (fiber and matrix) properties and incorporates composite-processing variables such as the fiber volume ratio, the void volume ratio, processing condition, and others.

Formulations of structural response based on simulated component information are viewed as mesostructural mechanics; those based on variables that describe the simulated component response are viewed as microstructural mechanics. These two examples are generic and apply to other situations, such as (1) coupon testing versus granular materials structure, (2) granular structure versus metallurgical formulations, (3) polymer chains versus physical chemistry formulations, and (4) structural system response versus finite-element formulations. A new, more generic paradigm is telescoping scale mechanics formulations based on elemental-level variables and the subsequent propagation of that information to any progressively higher observation scale by the recursive application of laminate theory (ref. 2).

A representative example of telescoping scale mechanics is composite mechanics, which is performed by repeated application of laminate theory from the fiber slice scale (fiber substructuring), where environmental and local fiber architecture effects are included, to ply scale and laminate scale. The main advantage of telescoping scale mechanics is that it bypasses classical differential and integral calculus, although it requires computer codes to perform simulation effectively. The objectives of this report are to describe telescoping scale mechanics and to demonstrate its generic features by using it to predict information observed at different hierarchical scales (ply laminate, structure) in five sample cases: (1) homogeneous composites, (2) hybrid composites, (3) smart composites, (4) composite-enhanced reinforced concrete structures, and (5) particulate composites. These are described with the governing equations and typical results. It is important to note that telescoping scale mechanics is only viable by computational simulation. The focus of this work is on what can be done rather than on specific details of the process.

Telescoping Mechanics

To describe telescoping mechanics for the simulation of composite behavior, it is helpful to define the multiple scales inherent in composites. Herein, composite scale refers to both substructuring (differential line) and telescoping (integration line). Composite scale substructuring refers to the substructuring of a laminate progressively to lower consistent scales through the thickness: multiple-fiber ply, single-fiber ply through the thickness of a ply, unit cell, and single-fiber slicing (fiber substructuring by slicing within a single fiber). Scale telescoping reverses the process of substructuring. Either scale direction can be simulated by the recursive application of laminate theory. This concept of telescoping mechanics is illustrated schematically in figure 1.

Starting with laminates, it is possible to progressively substructure (decompose) to lower scales of laminate behavior under stresses and strains. However, it is not easy to substructure laminate behavior in terms of mechanical, thermal, or other properties. Any behavior from the highest scale to the lowest can be substructured with the use of consistent formal composite mechanics methods. Formal scale substructuring methods are the inverse of scale telescoping methods.

Figure 1 shows the various scales in the telescoping sequence: (a) the slice, whose scale is a fraction of the fiber diameter; (b) the single fiber embedded in a matrix (typical cell) with a scale equal to the fiber diameter plus some matrix; (c) the single-fiber typical cell when it telescopes into a multifiber ply with a scale of ply thickness; and (d) the multifiber ply when it telescopes into multi-ply laminate with a scale of laminate thickness. Other scales in the telescoping sequence up to the structural system scale (not shown in fig. 1) include the multilaminate finite element, the multifinite-element subcomponent, the multisubcomponent component, and the multicomponent composite structural system. Scales (a), (b), (c), and (d) are simulated by recursive laminate application (telescoping scale mechanics); the multilaminate finite element, the multifinite-element subcomponent, and the multisubcomponent component, being structural scales, cannot be simulated in this way.

The concept of scale telescoping by progressive laminate theory application is natural and has several advantages:

1. Elemental equations remain simple.
2. The computer keeps track of the information needed to propagate scale information to the next highest scale.
3. Laminate theory is widely used and extensively discussed in textbooks.
4. Environmental effects are easily incorporated at the scale they occur.
5. Fabrication processes are taken into account.
6. Nonlinear geometry and material behavior are incrementally simulated.
7. Time and related effects are also simulated incrementally or stated differently by updated Lagrangian methods.

Telescoping mechanics for composite behavior and composite mechanics will be used interchangeably in the following sections.

Homogeneous Composites

Homogeneous composites are defined herein as those made from one type of fiber in one type of matrix. They will be used as the basis to describe telescoping scale mechanics of the elemental slice, single-fiber cell, multifiber cell (single ply), and multi-ply laminate scales.

Elemental Scale

The selection of the elemental scale is critical in telescoping scale mechanics. The authors consider the fiber substructuring slice (fig. 1(a)) as the elemental scale to use for deriving the governing equations. If we assume that the slice consists of matrix, interphase, and fiber and that the behavior of the constituents is linear, the equation for the transverse modulus is

$$E_{22s} = \frac{E_{ms}E_{is}E_{fs}}{k_{ms}E_{is}E_{fs} + k_{is}E_{fs}E_{ms} + k_{fs}E_{ms}E_{is}} \qquad (1)$$

where E is the modulus of the constituent, k is the volume ratio of the same constituent in the slice, 22 is the slice modulus on plane 2 in the 2 direction, s is the slice, m is the matrix, i is the interphase, and f is the fiber. The slice volume ratios are determined from the specified fiber diameter, average composite volume ratio, type of fiber distribution array, size (thickness or volume ratio) of the interphase, and number of slices in substructuring the fiber.

Equation (1) is simple but comprehensive because the matrix, voids, environmental effects, and interfacial disbonds or partial bonds can be included. Comparable equations can be written for other mechanical and thermal properties (ref. 3). The approach in reference 3 can be expanded to derive equations for bug-like properties.

The application of recursive laminate theory begins by stacking the slices and predicting the composite unit cell properties (schematic above slice, fig. 1(a)). The main advantage of this method is that all unit cell properties are predicted by the same assumed local uniformities or nonuniformities.

Single-Fiber Cell

Table I compares the composite ply properties predicted by the slicing approach with those predicted by methods based on the unit cell micromechanics equation shown below (ref. 4) and by three-dimensional finite-element methods (ref. 5). The comparisons range from good to very good except for the shear moduli (no explanation). In addition to being inclusive and simple, the comparisons demonstrate the effectiveness of recursive laminate theory at the fiber subscale level. Note that elements were applied in series at the slice level and in parallel at the slice stack; a form of trapezoidal numerical integration of the stacking process to represent the single-fiber cell was assumed in the derivation of equation (2):

$$E_{l22} = \frac{E_m}{1 - \sqrt{k_f\left(1 - \frac{E_{f22}}{E_{m22}}\right)}} \qquad (2)$$

Multifiber Ply

Commercially available tapes normally have a partially cured thickness of one ply (lamina). This includes about 15 fibers through the thickness (glass, graphite, or Kevlar). Through-the-thickness nonuniformities are represented by substructuring each of the 15 fibers into slices and then stacking them again by applying laminate theory. The results from two other micromechanics methods (fig. 2) are compared in figure 3 for mechanical properties and in figure 4 for thermal properties. Note that comparisons show three different computer codes: the Integrated Composite Analyzer (ICAN, ref. 6), Metal Matrix Composite Analyzer (METCAN, ref. 7), and Ceramic Matrix Composite Analyzer (CEMCAN, ref. 3). The ICAN and METCAN codes are based on square area unit-cell micromechanics, but METCAN also includes the interphase. The CEMCAN code is based on the fiber substructuring slice. The comparisons are good, especially between CEMCAN and METCAN.

Multi-Ply Laminate or Composite

The governing equations for simulating plate-like laminate behavior in array form are

$$\begin{Bmatrix} \varepsilon_{co} \\ \kappa_c \end{Bmatrix} = \begin{bmatrix} A_c & B_c \\ B_c^T & D_c \end{bmatrix}^{-1} \left\langle \begin{Bmatrix} N_{ca} \\ M_{ca} \end{Bmatrix} - \begin{Bmatrix} N_{ct} \\ M_{ct} \end{Bmatrix} - \begin{Bmatrix} N_{cm} \\ M_{cm} \end{Bmatrix} \right\rangle \tag{3}$$

where ε refers to referenced plane strains; *A*, *B,* and *D* refer to axial, coupling, and bending stiffnesses, respectively; *N* is in-plane forces; κ is curvatures; *M* is bending moments; *c* is the laminate property; *o* is the reference plane; *a* is applied ( ); *t* is the temperature; and *m* is the moisture. The elements of the arrays and vectors on the right side of equation (3) are evaluated by applying conventional laminate theory (ref. 6) with ply properties. The laminate properties were obtained by three applications (slice, multifiber ply, multi-ply) of conventional laminate theory.

Equation (3) is used as input for the finite-element structural analysis of general composite plate-like structures (ref. 6). A typical result obtained from this type of composite structural analysis is shown in figure 5 along with measured data comparisons (ref. 8). The agreement is very good. Note that the recursive application of laminate theory is so generic that it simplifies the simulation of several other composite architectures, which will be described in the next section.

Applications With Hybrid and Smart Composites

The following examples show how the recursive application of laminate theory can simulate hybrid and smart composite behavior.

Hybrid Composites

There are two types of hybrid composites: interply (ply by ply) and intraply (tows of different fibers placed side by side in the same ply). Interply hybrid composites are comparable to homogeneous composites, but each ply is made from a different fiber and matrix. The recursive application of laminate theory to interply hybrids is identical to that already described. The structure of intraply hybrid composites is not comparable to homogeneous composites, as can be seen in figure 6 (ref. 9). This simulation requires additional laminate applications: two for the simulation of each intraply hybrid composite as an individual ply prior to laminate simulation, as contrasted to one for homogeneous composites.

The micromechanics equation for predicting the transverse modulus of an intraply hybrid composite is given by (ref. 10)

$$E_{HC2} = \frac{E_{mp}}{\left[1-k_{fp}\right]\left(1-\frac{E_{mp}}{E_{fp}}\right)+V_{sc}\left\{\frac{E_{mp}}{E_{ms}}\left[1-\sqrt{k_{fs}}\left(1-\frac{E_{ms}}{E_{f2s}}\right)\right]-\left[1-k_{fp}\left(1-\frac{E_{mp}}{E_{f2p}}\right)\right]\right\}} \tag{4}$$

where E is the ply modulus, k is the fiber volume ratio, H is the hybrid, C is the composite, f is the fiber, p is the primary composite, m is the matrix, and s is the secondary composite. Predictions obtained from equation (4) are compared with more approximate equations, the recursive laminate theory, the two-dimensional finite element, and the measured data in table II (ref. 10).

Additional predictions of properties with the use of telescoping scale mechanics for intraply hybrid composites are shown in figure 7 (ref. 9). Considering the computational speed with which they were obtained, the comparisons are very good. Collectively, the comparisons in table II and figure 7 demonstrate the computational expediency, generality, and versatility of telescoping scale mechanics with the recursive application of conventional laminate theory.

Smart Composites

The procedure used in telescoping scale mechanics for simulating the behavior of smart composite and laminate structures is similar to that used for hybrid composites. The intraply or interply hybrid composite concept is adapted to smart composite structures. Intraply hybrid composites are made by intermixing different fibers in the same matrix and the same ply. Interply hybrid composites have plies made from a different fiber matrix. A schematic of a unidirectional intraply hybrid composite is shown in figure 6. For further discussion see references 9 and 10.

A smart composite structure consists of smart material (fiber-like sensors and actuators) embedded preferably in the same matrix to replace the secondary composite in the intraply hybrid (schematic, fig. 8). Telescoping scale mechanics treats the sensors and actuators like other intraply hybrids, but with the properties of the smart material. Note that different smart materials can be used for different plies, depending on the design requirements. Plies with smart materials can then be handled as interply hybrids, and the same telescoping scale mechanics can be applied to simulate their behavior. The secondary composite is replaced by a smart or adaptive device for either sensor or actuator, or both. The geometric concept is schematically illustrated in figure 8, and the corresponding intraply hybrid representation is shown in figure 9 (ref. 11). Typical results obtained from reference 11 when 0º plies are controlled by smart material are shown in table III, and those obtained when +45º plies are controlled by smart material are shown in table IV. Central magnitudes can be selected to reduce stress to the desired magnitudes. Evaluations of this type are difficult to achieve as readily with conventional composite mechanics, including the commonly used laminate theory or any other formulations.

Composite-Enhanced Reinforced Concrete Structures

Telescoping scale mechanics is also applicable to the hierarchical simulation of composite-enhanced reinforced concrete infrastructures (ref. 12). A typical cross section of two reinforced concrete structural members is shown in figure 10. Note that the fiber composite laminate is placed at the bottom to restore or enhance the tensile strength of these sections. The section properties required for finite-element structural analysis are obtained by telescoping scale mechanics of the layered section. The scale hierarchy includes fiber composite enhancement, single or two-way steel reinforcement with concrete, and several concrete layers. The concrete properties are simulated by applying particulate telescoping scale mechanics first to cement, sand, and then gravel (ref. 13). These concrete properties are then used with reinforced steel bars to simulate the layer as a ply in the composite scale telescoping hierarchy.

Other Higher Scales

The next scale in the structural hierarchy is the finite element. A schematic of a finite-element model for a reinforced concrete arch with composite enhancements is shown in figure 11 (ref. 12). Note the three different structural sections and the tapering width of the arch. Each finite element constitutes a structural mesoscale and has a different meso structure and different stiffness properties, consistent with the previously stated definition. All finite elements form the structure and therefore the structural scale, which is the highest scale in the structural scale telescoping hierarchy.

Progressive fracture is employed to evaluate the strength enhancement and structural damage tolerance of the arch attributable to enhancement with the use of composite layers. A schematic of progressive fracture simulation is shown in figure 12. Note that hierarchical scale telescoping starts with the cement and sand "nanoscale" and ends at the microstructural scale (left side of figure). Also, hierarchical scale telescoping is essential to synthesize gravel structural properties. Progressive hierarchical scale substructuring (decomposition, right side of figure) starts from the structural scale and ends at the nanoscale, where damage initiation, growth, and progression are identified and tracked. Typical results are shown in figure 13 (ref. 12). As can be seen, composite laminate placed at the bottom layer provides the most effective enhancement. Progressive fracture to evaluate strength enhancement of composite-repaired or enhanced reinforced concrete structures is useful for illustrating the hierarchy of various composites, and structural scales and telescoping scale mechanics.

Conclusions

Telescoping scale mechanics is used with the recursive application of laminate theory to develop formulations based on the lowest possible elemental-scale equations for all composite properties. Composite behavior is then synthesized by recursive application of laminate theory up to the laminate scale. The laminate response is decomposed to lower scales by progressive laminate substructuring using laminate theory. Typical results are compared with those obtained from other methods, such as single-cell micromechanics and two- or three-dimensional finite-element analysis. These comparisons demonstrate the relative inclusiveness, accuracy, and computational effectiveness of a telescoping scale for composite mechanics. Additional results from homogeneous, hybrid, smart, and particulate composites and from composite-enhanced reinforced concrete structures illustrate the generality and versatility of the method. These results show that laminate theory is an efficient computational algorithm for composite mechanics and for homogeneous materials that experience progressive, through-the-thickness, nonlinear behavior as well.

Appendix—General Remarks

Frequent reference is made herein to (1) hierarchical scales, (2) progressive telescoping or substructuring, (3) telescoping scale mechanics, and (4) telescoping scales. Both major and subtle distinctions are drawn between these terms, even though they may sound similar to those unfamiliar with the reported work. The following remarks explain how they have been specifically used herein.

Hierarchical scale (refs. 1 and 13) denotes the sequential representation of scales in composites such as micro, ply, laminate, component, finite element, substructural, and structural. However, it does not use recursively the laminate computational algorithm for all scales.

Progressive telescoping (ref. 2) scales describes formulations that start with the smallest reference scale and progressively synthesize specific behavior to higher scales. Scale *substructuring* formulations start with the largest scale and progressively decompose the response to lower scales. Composite mechanics includes both. The subtle difference is that the fundamental scale uses simple equations, and telescoping and composite mechanics do not.

Telescoping scale mechanics (ref. 12) denotes hierarchical scale telescoping or decomposition by recursive application of laminate theory alone, without any recourse to additional formulations for different scales. The first (fundamental) scale is based on micromechanics equations.

Telescoping scale (ref. 3) denotes basic formulations at the lowest scale of a particulate (particle-like nonfiber) composite with triphase constituents. The basic formulation homogenizes the tri-phase constituents into a matrix. This matrix is used with the next scale particulates and their respective interphase to homogenize the composite, and so on, until the largest scale particulate has been homogenized. In this use the basic formulation is the same, but the variables in it change to represent the scale to which they are applied. Scale telescoping is akin to fractals, because progressive homogenization explicitly recognizes the variables of each scale up to the present scale.

Though results are not presented here, telescoping scale mechanics are equally applicable to homogeneous materials that experience progressive, through-the-thickness, nonlinear material behavior (ref. 14), to structural sandwiches (ref. 15), to three-dimensional fiber-reinforced composites (ref. 16), and to woven fabric composites (ref. 17). Simulations for these are more subtle and require innovative thinking.

References

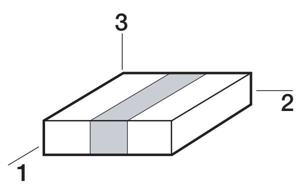
1. Chamis, C.C.: Mechanics of Composite Materials: Past, Present, and Future. J. Compos. Technol. Res., vol. 11, no. 1, 1989, pp. 3–14.
2. Mital, S.K.; Murthy, P.L.N.; and Chamis, C.C.: Concrete Thermomechanical Behavior Via Telescoping—Scale Mechanics, invited paper for the Prager Symposium to honor Professor Z.P. Bazant 33rd Annual Technical Meeting of the Society of Engineering Science, Tempe, Arizona, October, 1996.
3. Murthy, P.L.N.; and Chamis, C.C.: Towards the Development of Micromechanics Equations for Ceramic Matrix Composites via Fiber Substructuring. NASA TM–105246, 1992.
4. Chamis, C.C.: Simplified Composite Micromechanics Equations for Hygral, Thermal, and Mechanical Properties. SAMPE Q., 1984, pp. 14–23.
5. Caruso, J.J.; and Chamis, C.C.: Assessment of Simplified Composite Micromechanics Using Three-Dimensional Finite-Element Analysis. J. Compos. Technol. Res., vol. 8, 1986, pp. 77–83.
6. Murthy, P.L.N.; and Chamis, C.C.: Integrated Composite Analyzer (ICAN), Users and Programmers Manual. NASA TP–2515, 1986.
7. Hopkins, D.A.; and Chamis, C.C.: A Unique Set of Micromechanics Equations for High Temperature Metal Matrix Composites. NASA TM–87154, 1985.
8. Chamis, C.C.: Vibration Characteristics of Composite Fan Blades and Comparison with Measured Data. Aircraft, vol. 14, no. 7, 1977, pp. 644–647.
9. Chamis, C.C.; Lark, R.F.; and Sinclair, J.H.: Mechanical Property Characterization of Intraply Hybrid Composites. NASA TM–79306, 1979.
10. Chamis, C.C.; and Sinclair, J.H.: Micromechanics of Intraply Hybrid Composites: Elastic and Thermal Properties. NASA TM–79253, 1979.
11. Shiao, M.C.; Singhal, S.N.; and Chamis, C.C.: Probabilistic Assessment of Uncertain Adaptive Hybrid Composites. NASA TM–106515, 1992.
12. Chamis, C.C.; and Gotsis, P.K.: Laminate Analogy for Composite Enhanced Concrete Structures. J. Ad. Mat., vol. 29, no. 1, Oct. 1997, pp. 3–10.
13. Mital, S.K.; and Chamis, C.C.: Thermal and Mechanical Behavior of Particulate Composite Materials. ASME PD, vol. 62, 1994, pp. 275–283.
14. Chamis, C.C.; and Minnetyan, L.: Progressive Fracture Structural Analysis of Wind Tunnel Structures. Part 3, AIAA Paper 97–1189, 1997, pp. 2284–2294.
15. Chamis, C.C.; Aiello, R.A.; and Murthy, P.L.N.: Fiber Composite Sandwich Thermostructural Behavior: Computational Simulation. J. Compos. Technol. Res., vol. 10, no. 3, 1988, pp. 93–99.
16. Mauget, B.R.; Minnetyan, L.; and Chamis, C.C.: Large Deformation Nonlinear Response of Soft Composite Structures via Laminate Analogy. Reprinted from the Eighth Japan/U.S. Conference on Composite Materials, Sept. 24–26, 1998.
17. Mital, S.K.; Murthy P.L.N.; and Chamis, C.C.: Simplified Micromechanics of Plain Weave Composites. J. Adv. Materials, vol. 33, no. 3, July 2001, pp. 10–17.

TABLE I.—SINGLE-FIBER CELL COMPARISONS
[AS-graphite fiber and intermediate modulus epoxy; fiber volume ratio, 0.62.]

Property	Three-dimensional finite element		Telescoping composite mechanics
	Multicell	Unit-cell square array	
Moduli, Mpsi			
Longitudinal (11)	19.5	19.5	19.5
Transverse (22)	1.24	1.22	1.22
Shear (12)	0.87	0.65	0.65
Shear (23)	0.61	0.38	.43
Poisson's ratio			
ν_{12}	0.25	0.32	.25
ν_{23}	0.26	0.37	.30

[a]These relatively large differences result from difficulties in determining proper boundary conditions to represent classical shear definitions.

TABLE II.—COMPARISON SUMMARY OF THERMAL AND ELASTIC PROPERTIES OF INTRAPLY HYBRID COMPOSITES



Property and units	Analysis method				Experimental
	Approximate (rule-of-mixtures)[a]	Telescoping composite mechanics[b]	Intraply hybrid micro-mechanics[c]	Finite element[d]	
Elastic modulus, 10^6 psi					
E_{HC1}	16.6	16.6	16.6		17.7
E_{HC2}	2.3	2.3	2.2	2.3	[e]1.7
E_{HC3}	2.3	2.3	2.3		
Shear modulus, 10^6 psi					
G_{HC12}	0.83	0.84	0.70		[e]0.90
G_{HC23}	.40	.40	.39	.40	
G_{HC13}	.83	.84	.84		
Poisson's ratio					
υ_{HC12}	0.25	0.24	0.25		0.30
υ_{HC32}	.48	.48	.48	.46	
υ_{HC13}	.25	.24	.27		
Stress, 10^6 in./in./°F					
Φ_{HC1}	0.68	0.51	0.52		
Φ_{HC2}	17.0	17.6	16.8		
Φ_{HC3}	17.0	17.6	17.4	17.1	

[a]Equations from ref. 1.
[b]Obtained using recursive laminate theory.
[c]Micromechanics equations from ref. 10.
[d]Finite-element analysis using NASTRAN.
[e]These relatively large differences result from difficulties in determining proper boundary conditions to represent classical shear definitions.

TABLE III.—PREDICTED MEAN PLY STRESSES WITH CONTROL IN 0° PLIES

Source	Ply orientation, deg											
	+45			–45			0			90		
	Mean ply stress, ksi											
	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S
External force	–61.8	–5.3	–1.1	–49.1	–3.6	0.8	–15.1	–3.1	0.1	–11.6	–0.6	0
Actuation strain	8.2	0.6	0.5	5.7	0.4	–0.4	–76.4	–12.5	0	2.3	0	0
Combined effect	–53.6	–4.7	–0.6	–43.4	–3.2	0.4	–91.5	–15.8	0.1	–9.3	–0.6	0

TABLE IV.—PREDICTED MEAN PLY STRESSES WITH CONTROL IN 45° PLIES

Source	Ply orientation, deg											
	+45			–45			0			90		
	Mean ply stress, ksi											
	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S
External force	–51.7	–7.3	–1.4	–53.8	–4.1	0.9	–23.2	–2.9	0	–13.3	–0.7	0
Actuation strain	–44.6	–8.6	2.1	33.1	2.5	–1.4	6.5	2.1	0	10.8	0.3	0+
Combined effect	–96.4	–15.9	0.7	–20.7	–1.6	–0.5	–16.7	–0.8	0	–2.5	–0.4	0

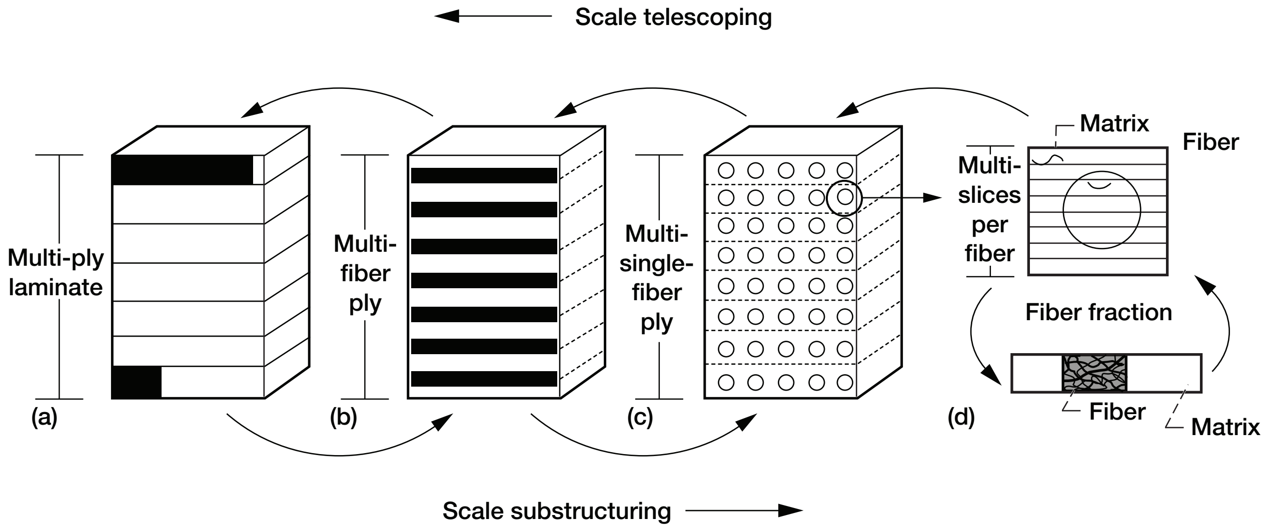


Figure 1.—Various scales in the telescoping sequence. (a) Multifiber ply after telescoping into multi-ply laminate. (b) Typical single-fiber cell after telescoping into multiple ply. (c) Single fiber embedded in matrix. (d) Slice.

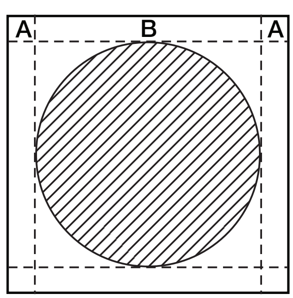
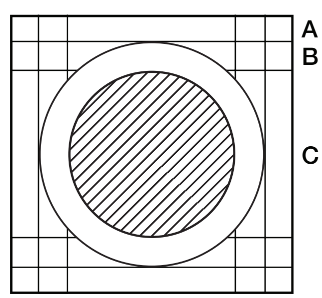
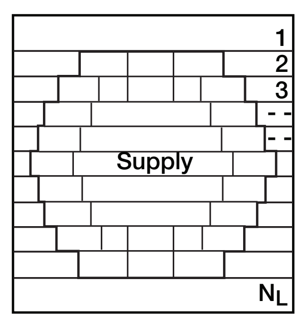
Polymer matrix composites (PMCs)	Metal matrix composites (MMCs)	Ceramic matrix composites (CMCs)
ICAN Integrated composites analyzer	METCAN Metal matrix composites analyzer	CECAN Ceramic matrix composites analyzer
 ICAN unit cell	 METCAN unit cell	 Unit cell with fiber, matrix, and interphase divided into N_L slices (subplies)

Figure 2.–Scale unit cell simulation.

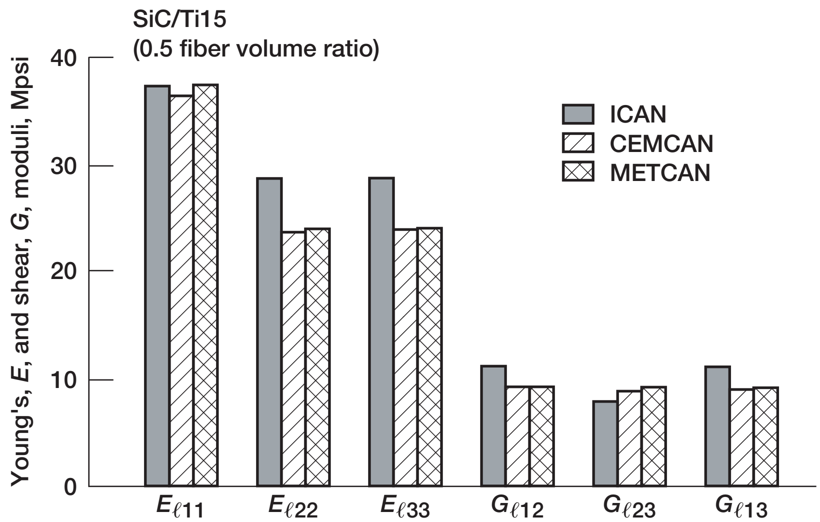


Figure 3.—Comparisons of ply mechanical properties from different scale simulations.

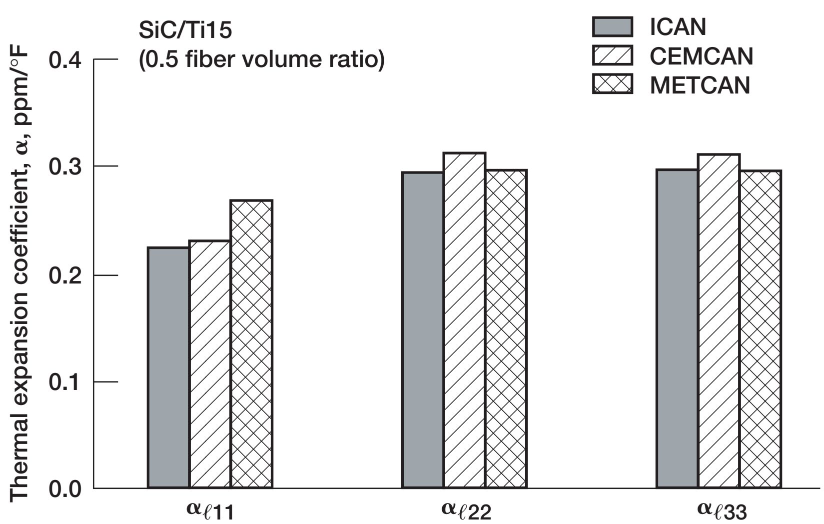


Figure 4.—Comparisons of ply thermal properties from different scale simulations.

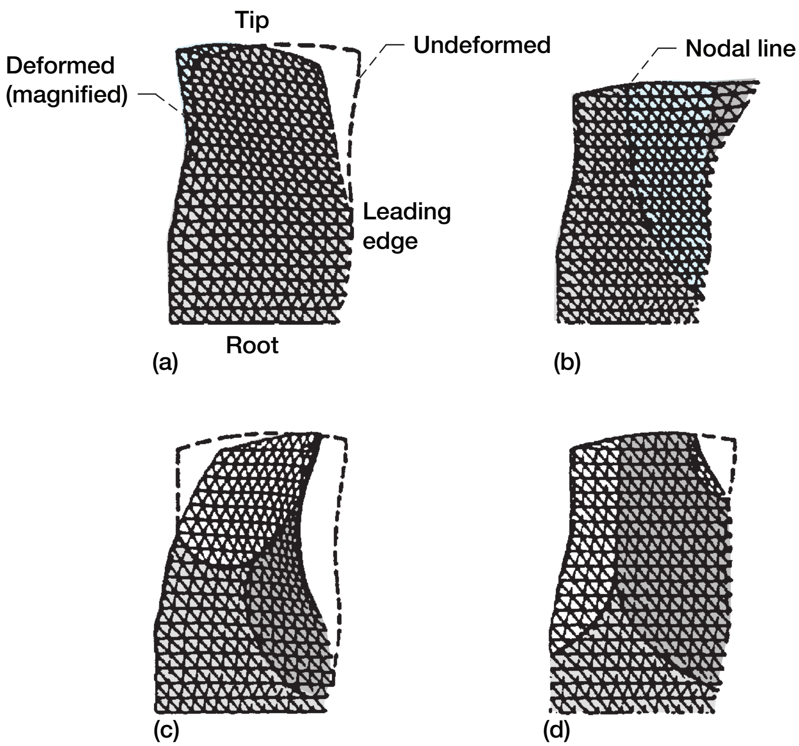


Figure 5.—Predicted and measured vibration mode shapes for high-tip-speed composite blade, HTS/K601 (∀40°, ∀20°, 0°). (a) Mode shape 1. Frequency, 290/294 Hz. (b) Mode shape 2. Frequency, 782/817 Hz. (c) Mode shape 3. Frequency, 912/932 Hz. (d) Mode shape 4. Frequency, 1258/1382 Hz.

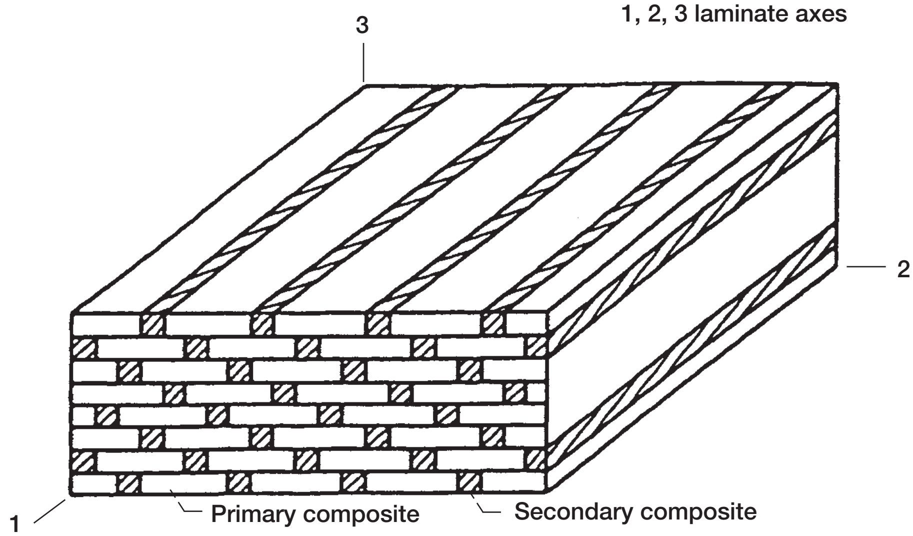


Figure 6.—Unidirectional intraply hybrid composite.

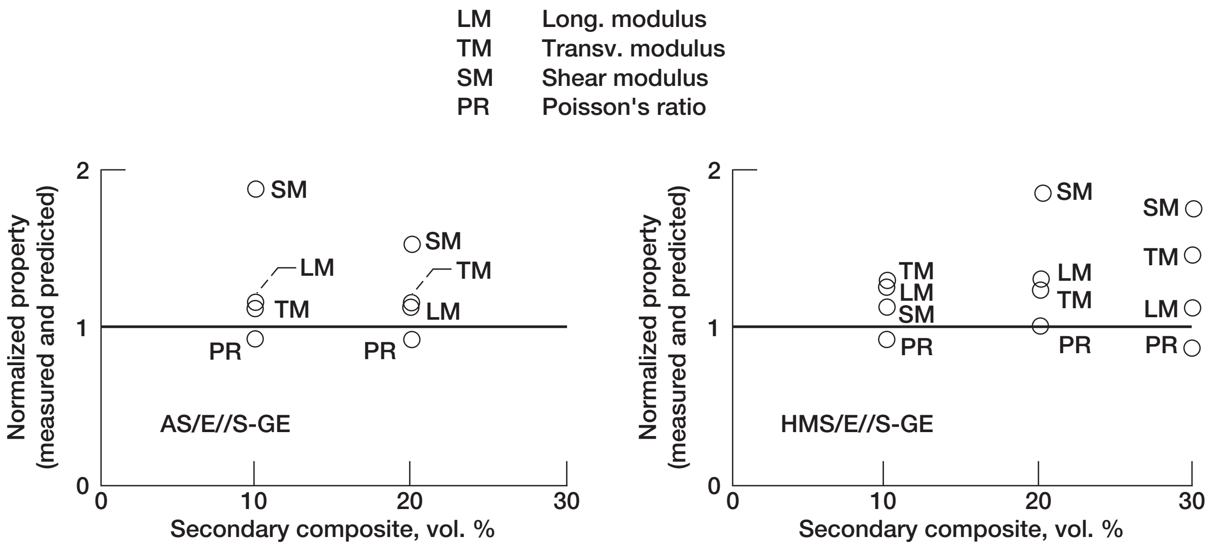


Figure 7.—Difficulties in imposing classical conditions during testing. Elastic property translation efficiency summary of intraply hybrids (graphite fiber composites hybridized with S-glass fiber composites; average of three replicates).

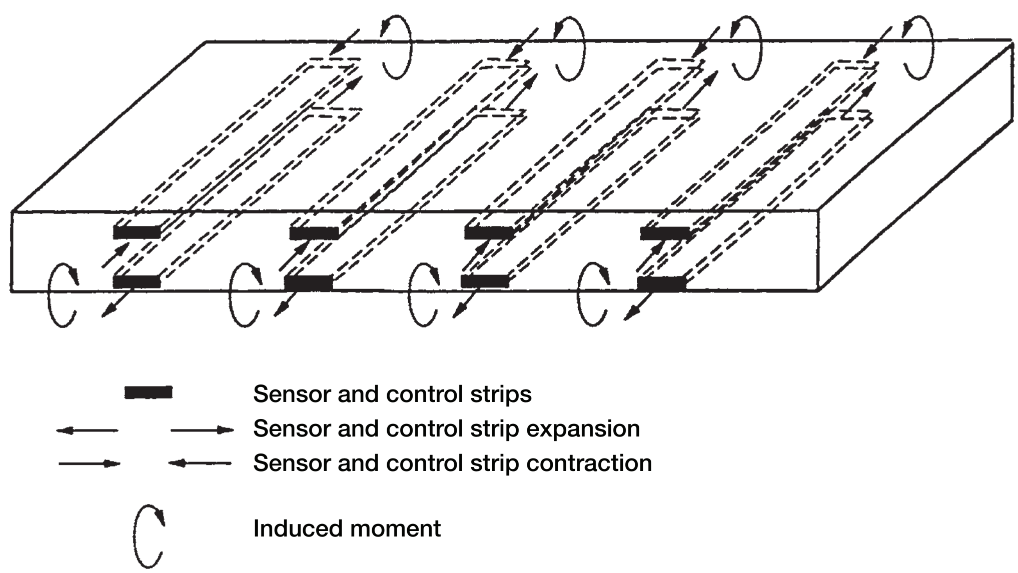


Figure 8.—Replacement of secondary composite with sensor or control materials represented by the intraply hybrid composite analogy.

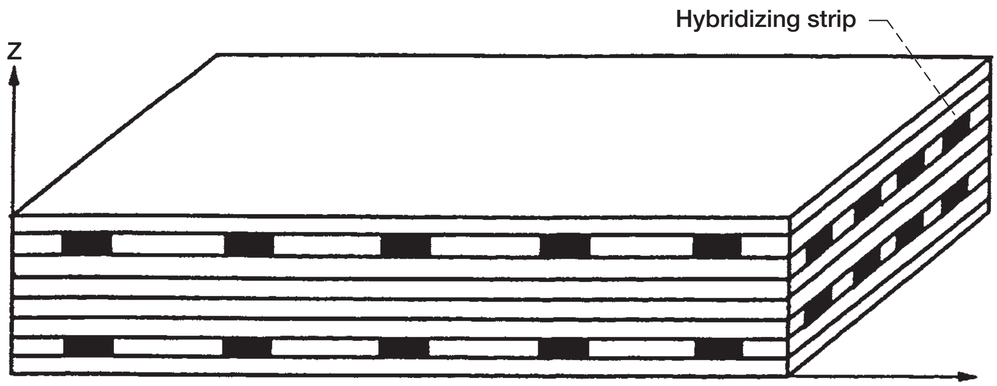


Figure 9.—Intraply hybrid composite system.

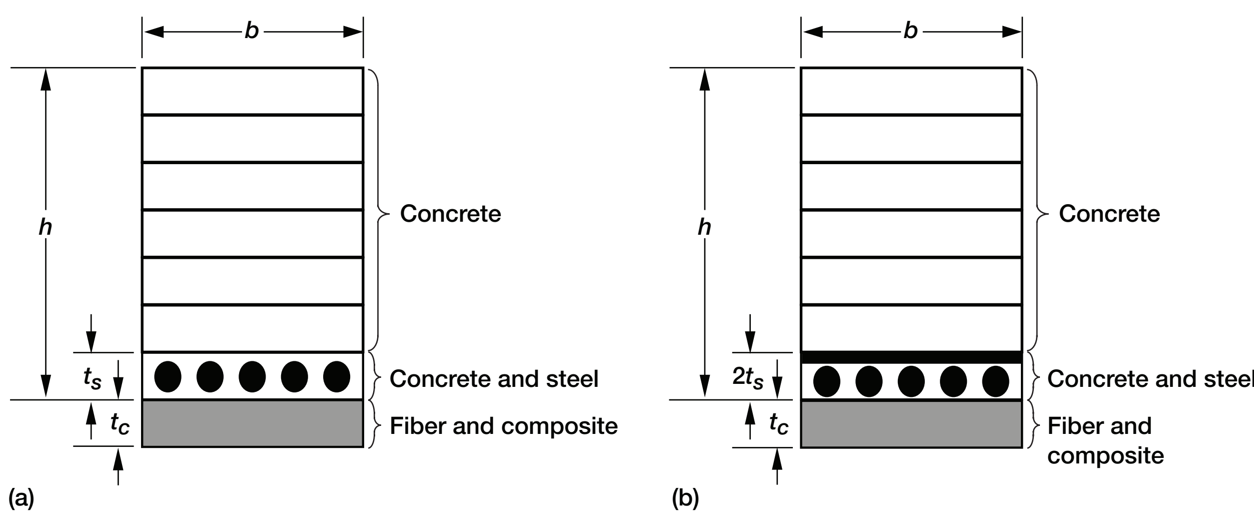


Figure 10.—Cross section of two reinforced concrete structural members. (a) One-way-reinforced section. (b) Two-way-reinforced section.

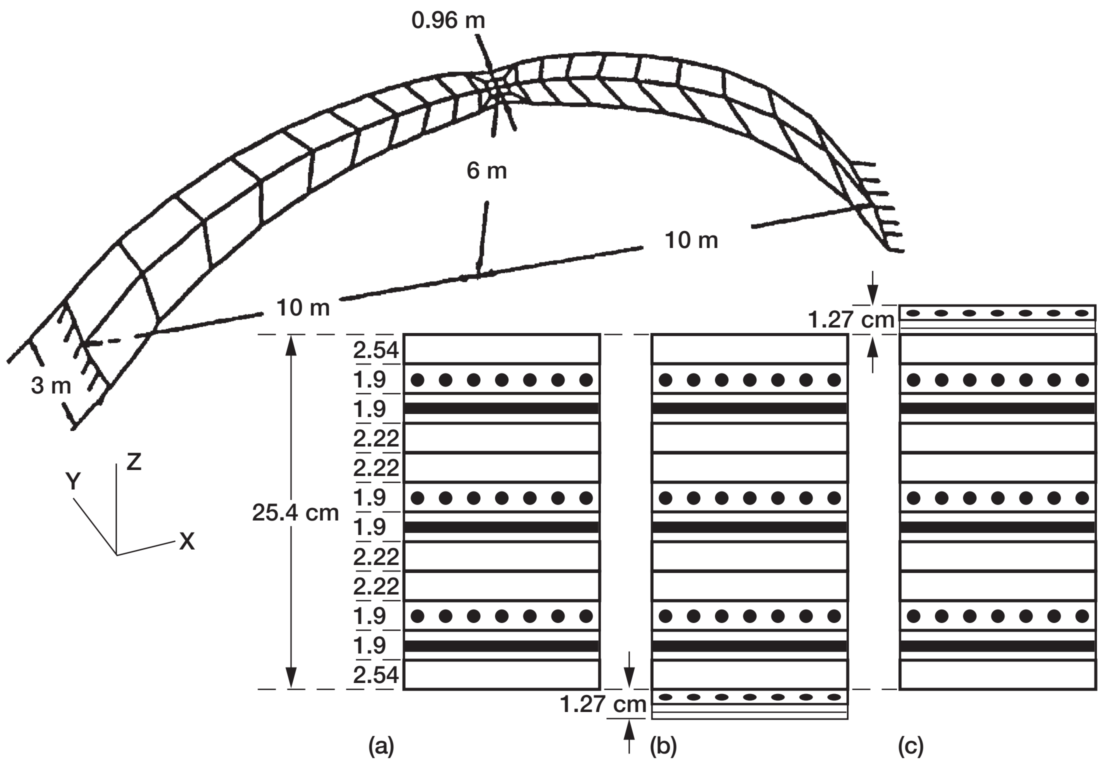


Figure 11.—Reinforced concrete arch with composite enhancements. (a) Unenhanced. (b) Enhanced at bottom. (c) Enhanced at top.

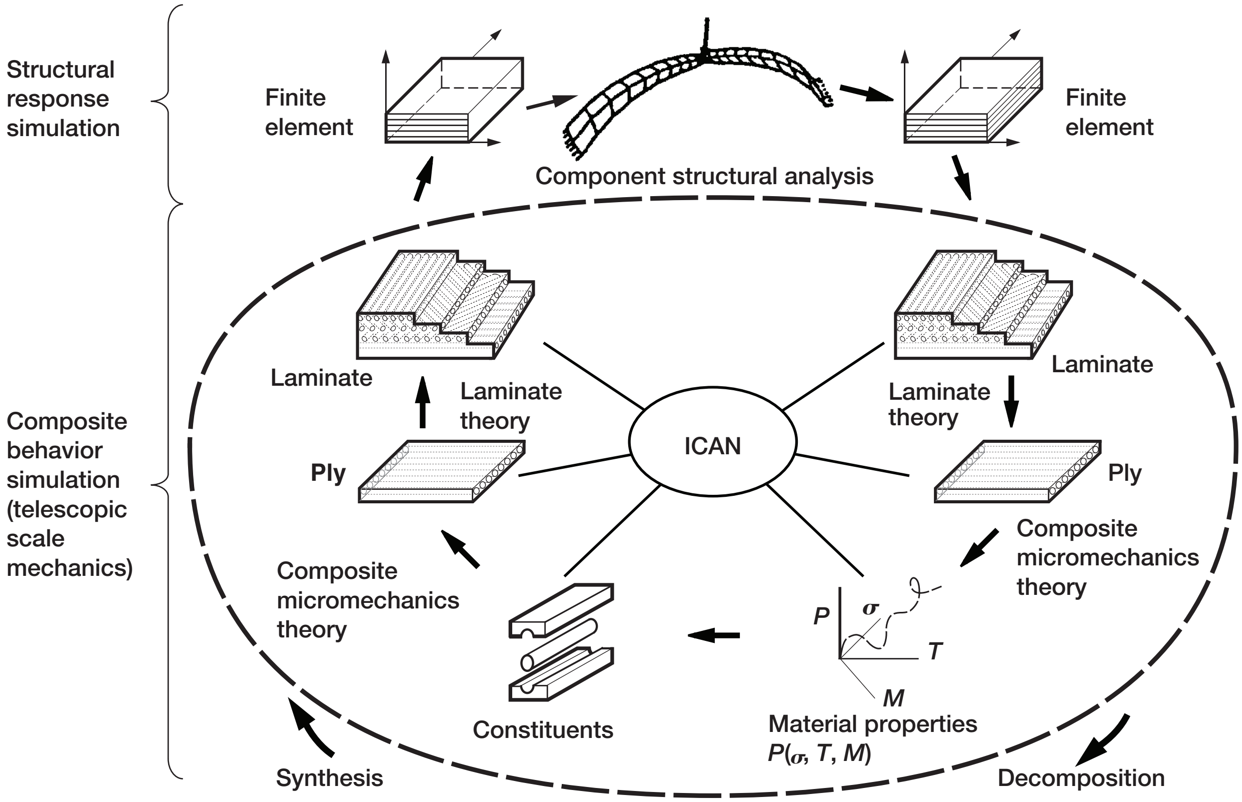


Figure 12.—Scale telescoping and scale substructuring for structural progressive fracture.

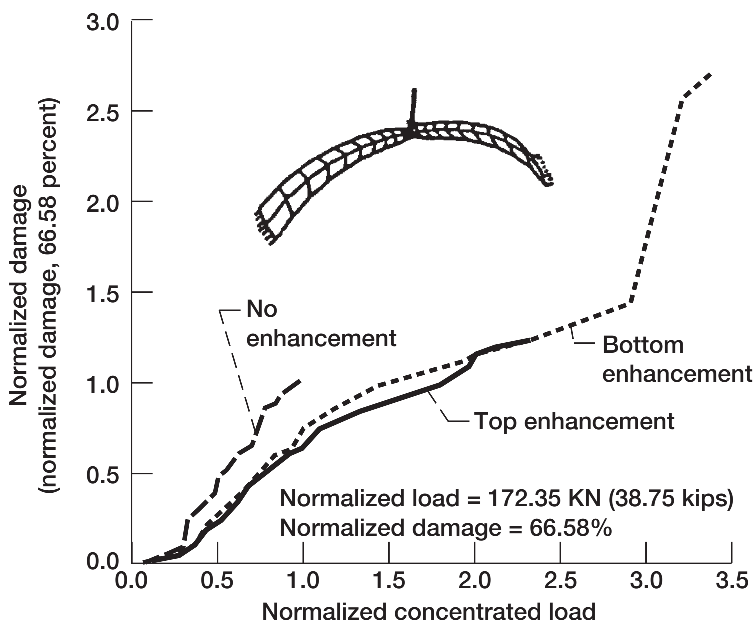


Figure 13.–Progressive structural fracture of a concrete-reinforced arch with and without composite enhancements (normalized load, 172.35 KN).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2004	Technical Memorandum

4. TITLE AND SUBTITLE

Telescoping Mechanics: A New Paradigm for Composite Behavior Simulation

5. FUNDING NUMBERS

WBS–22–708–48–11

6. AUTHOR(S)

C.C. Chamis, P.L.N. Murthy, P.K. Gotsis and S.K. Mital

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–11804

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2004-209317

11. SUPPLEMENTARY NOTES

C.C. Chamis, P.L.N. Murthy and P.K. Gotsis, NASA Glenn Research Center, and S.K. Mital, University of Toledo, Toledo, Ohio 43606. Responsible person, C.C. Chamis, organization code 5000, 216–433–3252.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 24 and 39 Distribution: Standard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report reviews the application of telescoping mechanics to composites using recursive laminate theory. The elemental scale is the fiber-matrix slice, the behavior of which propagates to laminate. The results from using applications for typical, hybrid, and smart composites and composite-enhanced reinforced concrete structures illustrate the versatility and generality of telescoping scale mechanics. Comparisons with approximate, single-cell, and two- and three-dimensional finite-element methods demonstrate the accuracy and computational effectiveness of telescoping scale mechanics for predicting complex composite behavior.

14. SUBJECT TERMS

Micro; Macro; Laminate; Hybrid; Infrastructures; Fiber composites; Micromechanics; Minimechanics; Laminate theory; Elemental scale; Unit cell; Hybrid composite; Smart composites; Finite element; Progressive fracture; Structural analysis; Reinforced concrete; Aging infrastructures; Infrastructure enhancement; Scale telescoping; Scale substructuring; Scale definition; Computational simulation

15. NUMBER OF PAGES

23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	